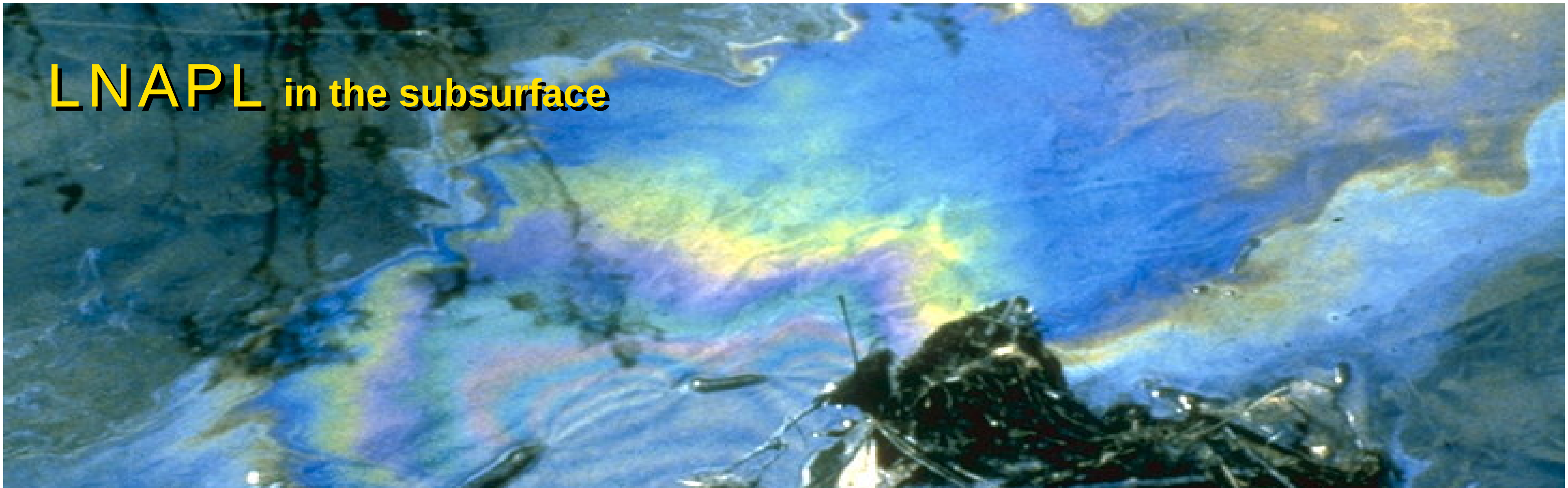

LNAPL Mobility and Well Thickness Variations

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&

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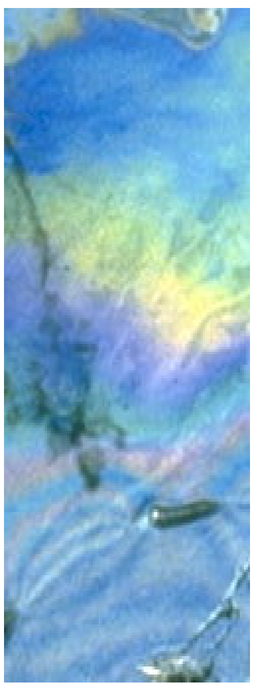
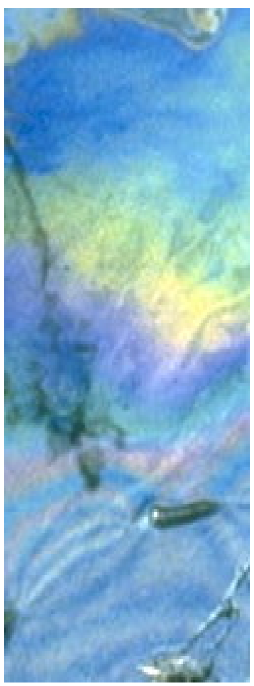
Presentation Outline

- LNAPL mobility
  - NAPL Hydraulic Conductivity
  - NAPL Relative Permeability
  - LNAPL Layer Transmissibility
- Potential for Lateral Migration
- Variable LNAPL Layer Thickness in Wells
  - Unconfined LNAPL
  - Confined LNAPL



LNAPL Mobility

- **Two Issues**
  - The soil “hydraulic conductivity” differs for different fluids
  - If multiple fluids are present in the pore space, each will have its “relative permeability” reduced



- **Scaling Hydraulic Conductivity**

$$\boxed{K_{ns} = K_{ws} \frac{\rho_r}{\mu_r}}$$

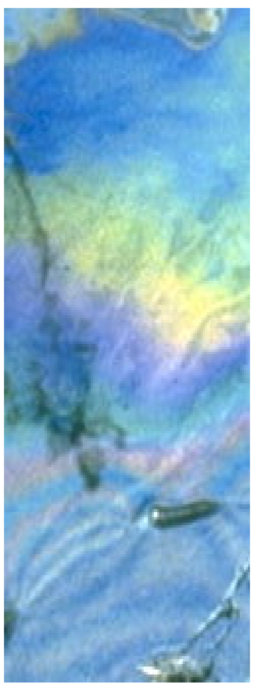
Relative Permeability

Darcy's Law:

$$q_n = K_{ns} \; k_{rn}(S_w, S_n) \; I_n$$

q_n **= Darcy velocity (volume flux)**

I_n **= LNAPL hydraulic gradient**

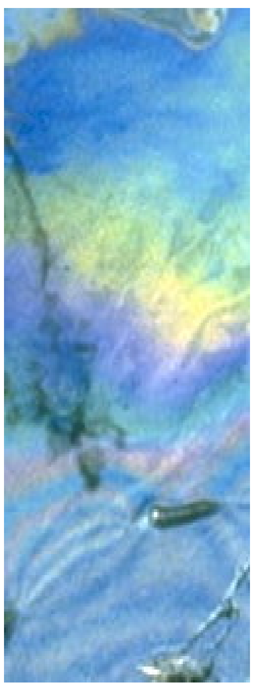


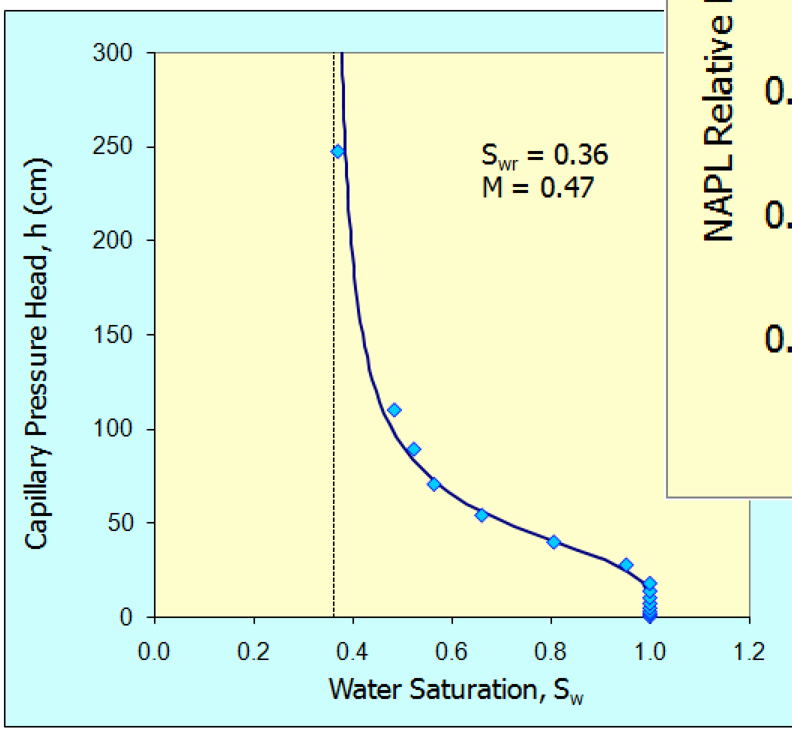
LNAPL Relative Permeability, k_{rn}

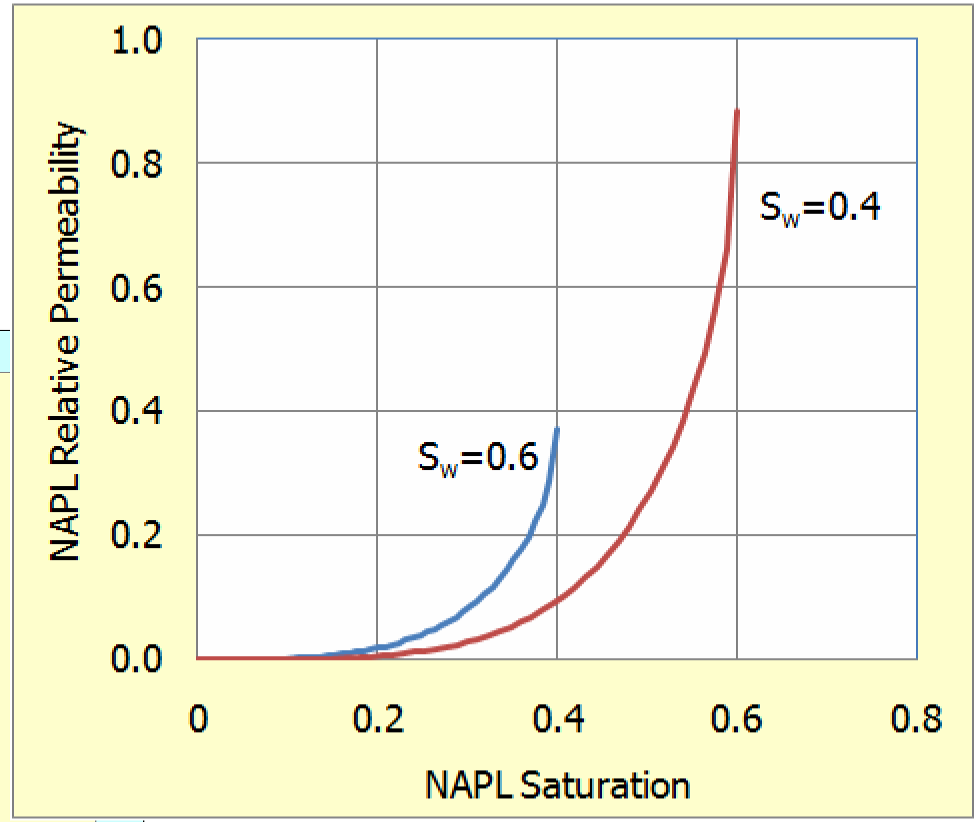
- **Varies from 0 to 1**
- **Depends on both water and LNAPL saturation**
- **Difficult to measure; most often calculated from soil characteristic curve**

Permeability Models

Soil from Mid-west Refinery located near Missouri river



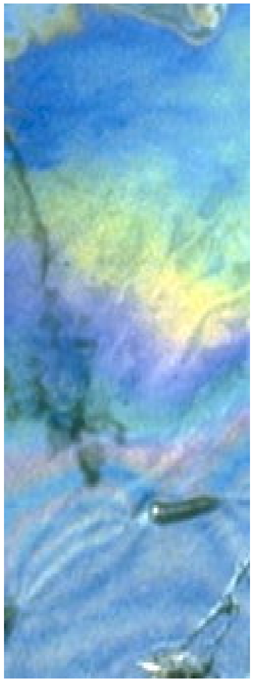




Relative permeability calculated using vanGenuchten-Burdine model equations

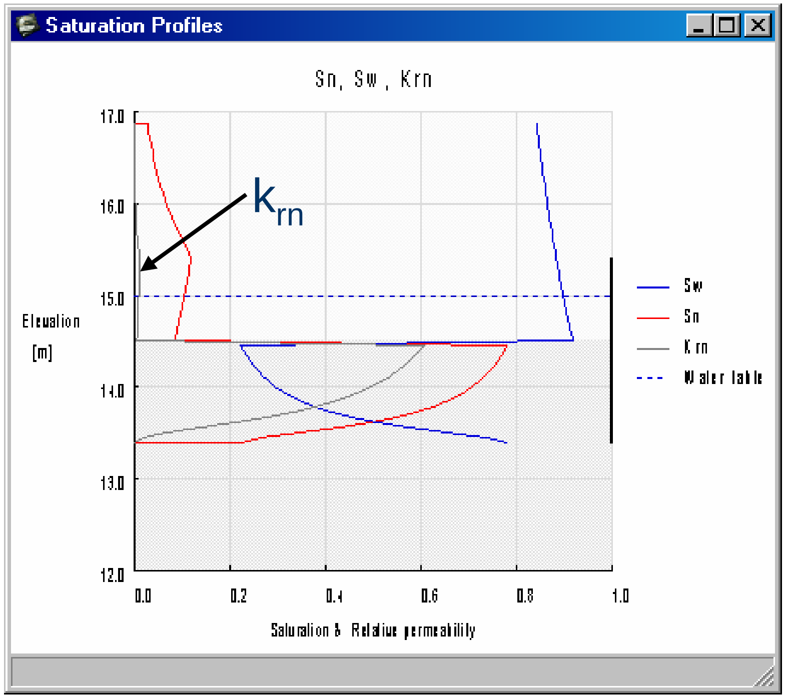
LNAPL-Layer Mobility, T_n

- **Primary factor controlling LNAPL lateral mobility is the layer transmissibility (transmissivity)**
- **Used in vertically averaged LNAPL models and other simplified models for LNAPL migration**
- **Field measurement using borehole (rate-of-rise) methods**

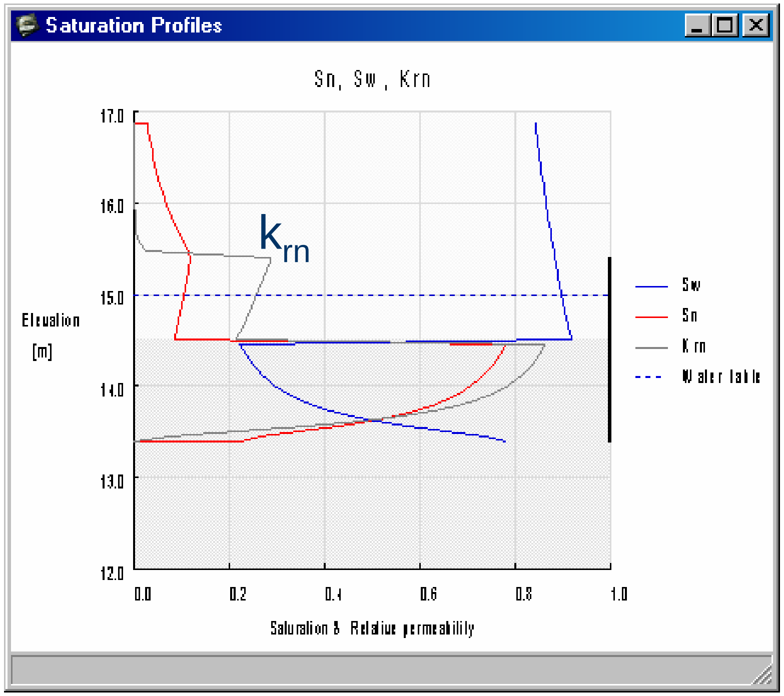


Comparison of Models

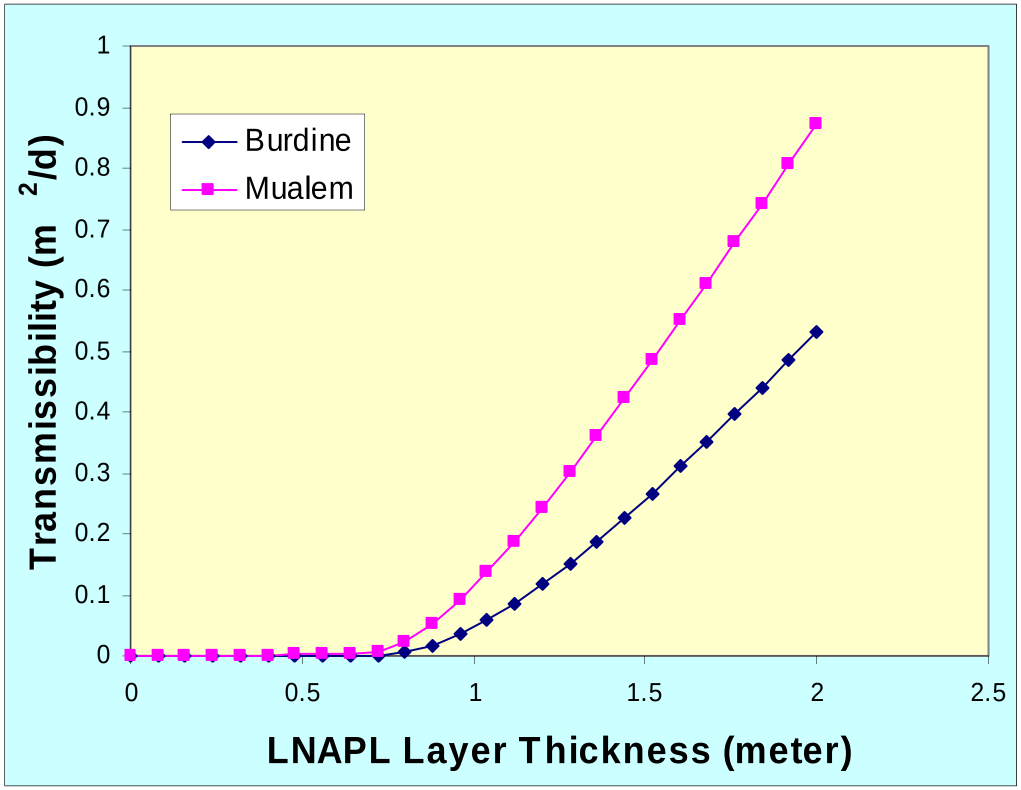
Burdine

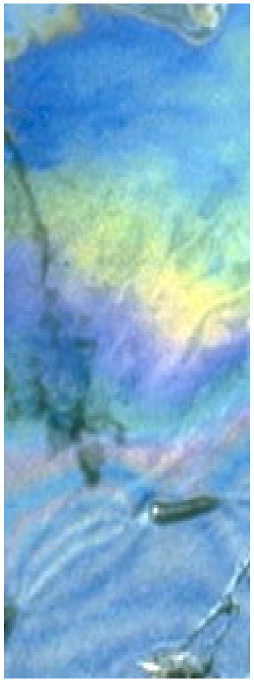


Mualem

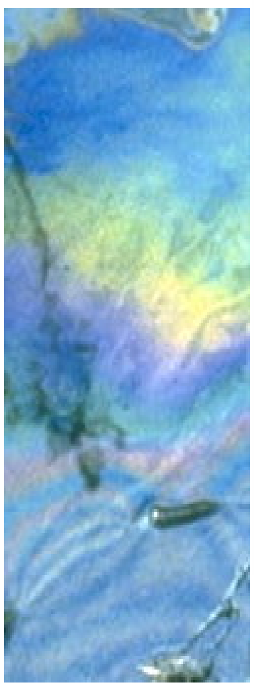


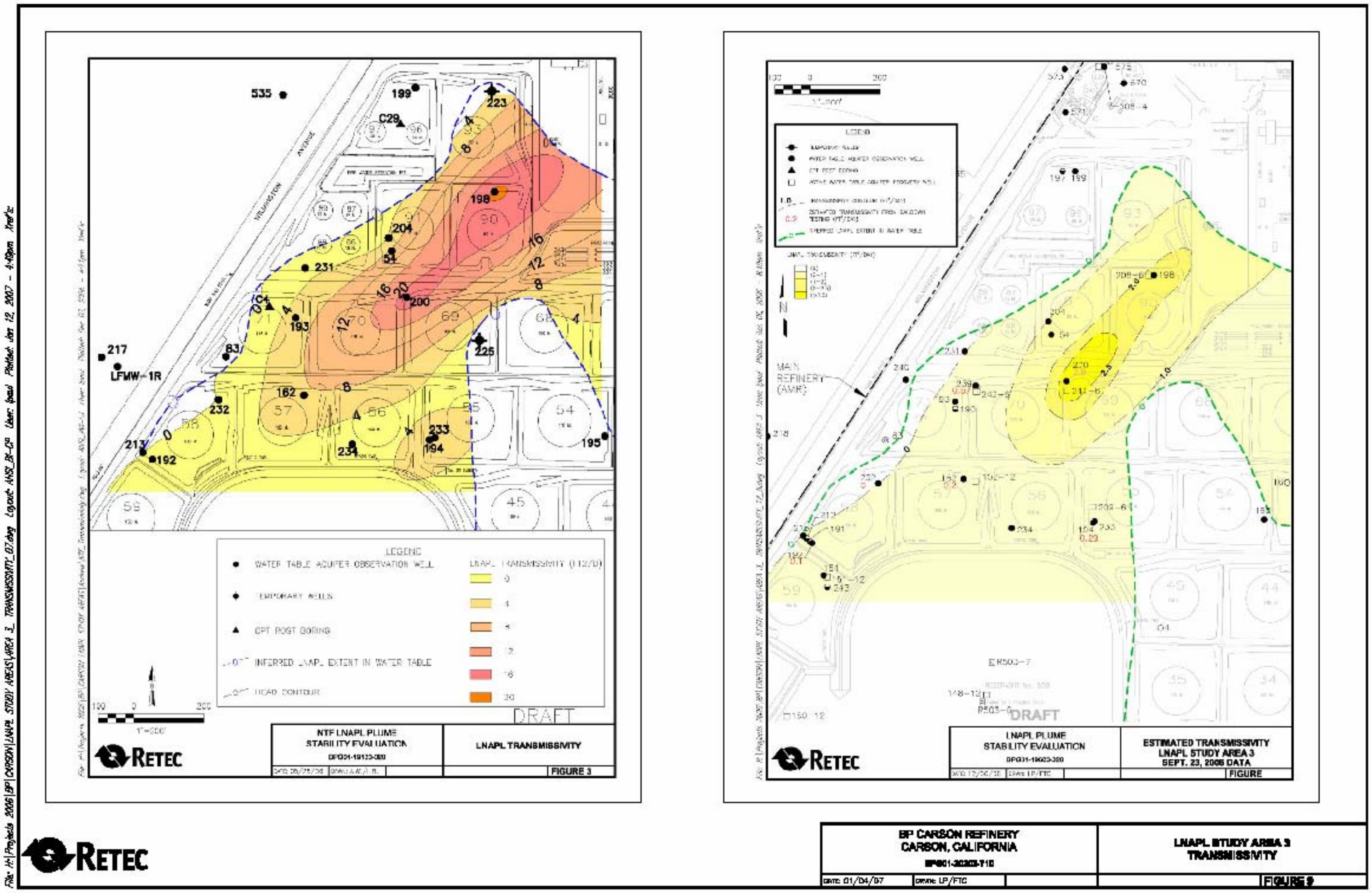
LNAPL Transmissibility, $T_n(b_n)$



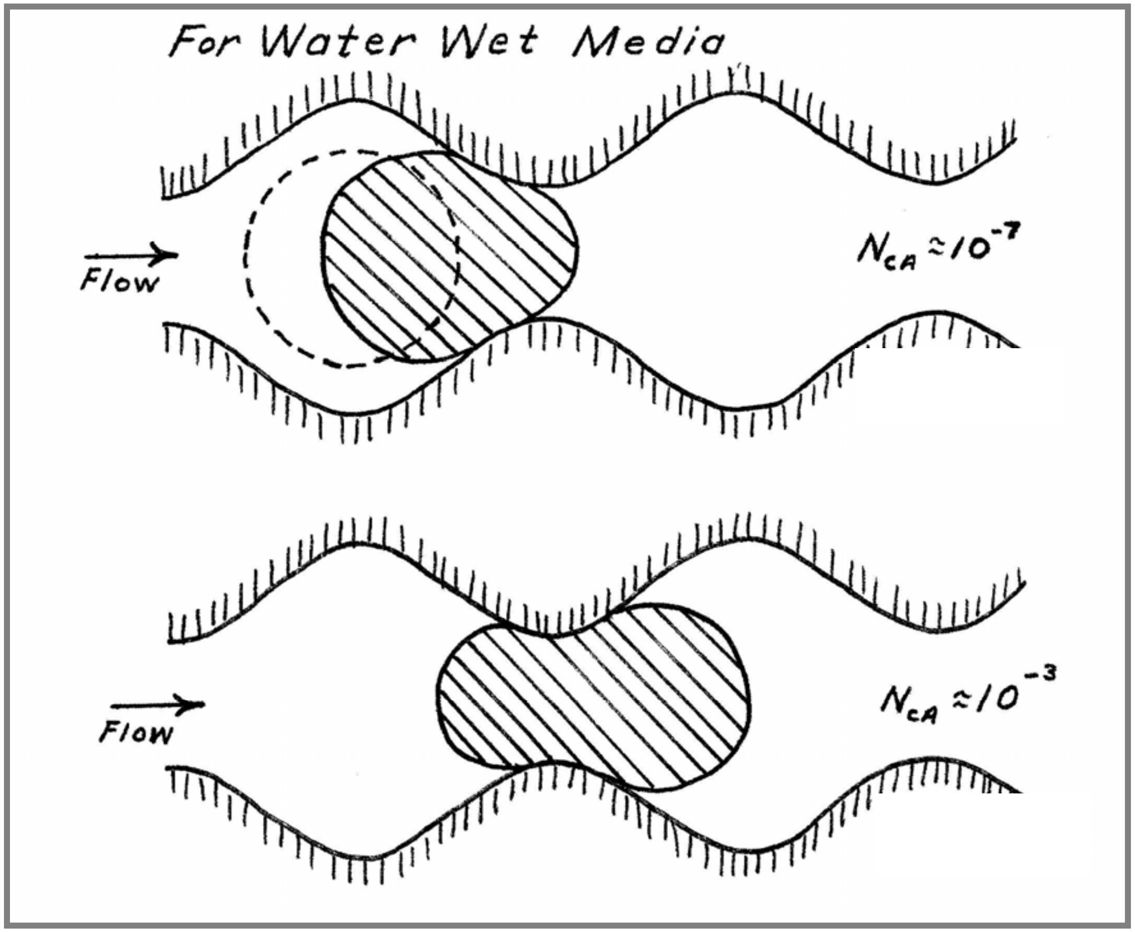


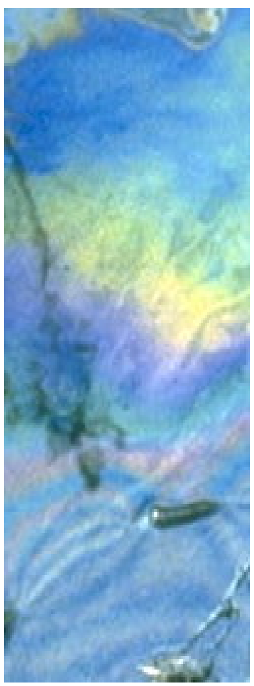
Field Assessment of Transmissibility





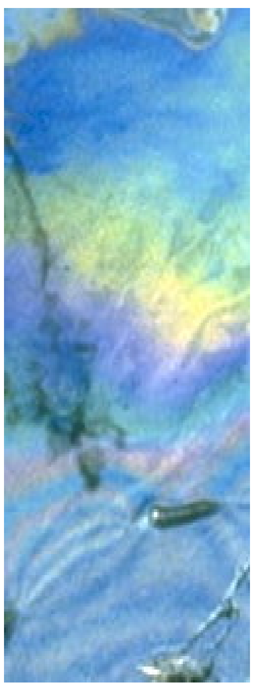
Movement of LNAPL into and out of pores – displacement entry pressure



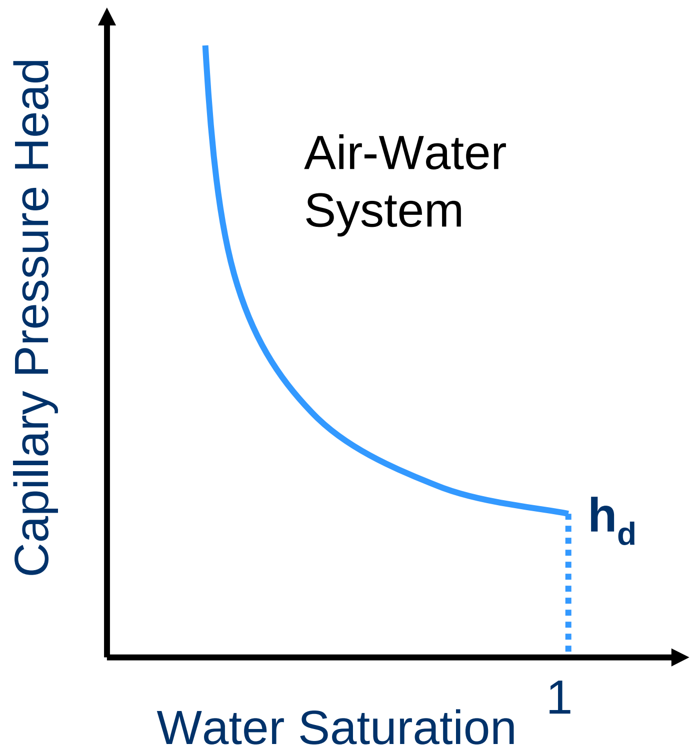


Entry Pressure and LNAPL Migration

- Water is the wetting fluid, LNAPL intermediate, and air is nonwetting
- Capillary pressure is necessary to cause displacement of wetting fluid from pore space by nonwetting fluid
- For LNAPL to migrate laterally, it must displace water from the pore space near the water table (within the capillary fringe)
- A minimum, critical LNAPL head, h_d, must be present near the edge of the plume in order to have spreading



Displacement Pressure Head, h_d

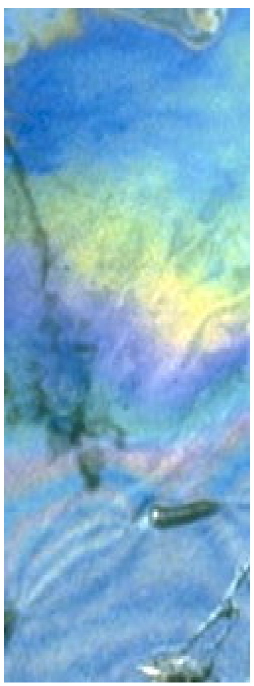


h_d also called:

- Entry pressure head
- Bubbling pressure head
- Capillary rise

Representative values from Lohman (1972):

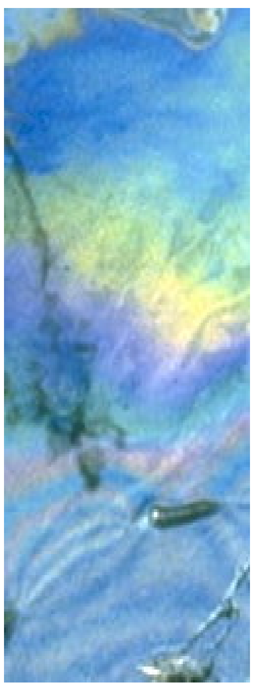
Material	Capillary Rise (cm)
Coarse sand	10
Fine sand	40
Silt	100



Critical LNAPL Well Thickness (for Spreading)

Approximate relationship (API, 1999)

$$b_{nc} = \left(\frac{\sigma_{nw}}{1-\rho_r} - \frac{\sigma_{an}}{\rho_r} \right) \frac{h_d}{\sigma_{aw}}$$



σ_{nw} - LNAPL-water interfacial tension

σ_{an} - air-LNAPL surface tension

σ_{aw} - air-water surface tension

ρ_r - LNAPL specific gravity (density ratio)

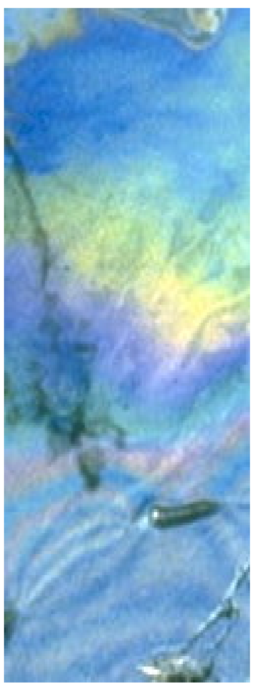
Example Calculation

Data: σ_{aw} = 65 dyne/cm; σ_{an} = 25 dyne/cm;

σ_{nw} = 20 dyne/cm; ρ_r = 0.75; h_d = 40 cm

$$b_{nc} = \left(\frac{20}{1-0.75} - \frac{25}{0.75}\right)\frac{40}{65} = 29\,cm$$

You could have approximately 30 cm of LNAPL in a monitoring well and the LNAPL plume would not be able to migrate laterally into uncontaminated locations



LNAPL Thickness in Wells

- In simple cases, correlates directly with LNAPL formation thickness
- In many cases, poor indicator of LNAPL conditions in formation

Monitoring Well LNAPL Thickness in a Sandstone (Unconfined Conditions)

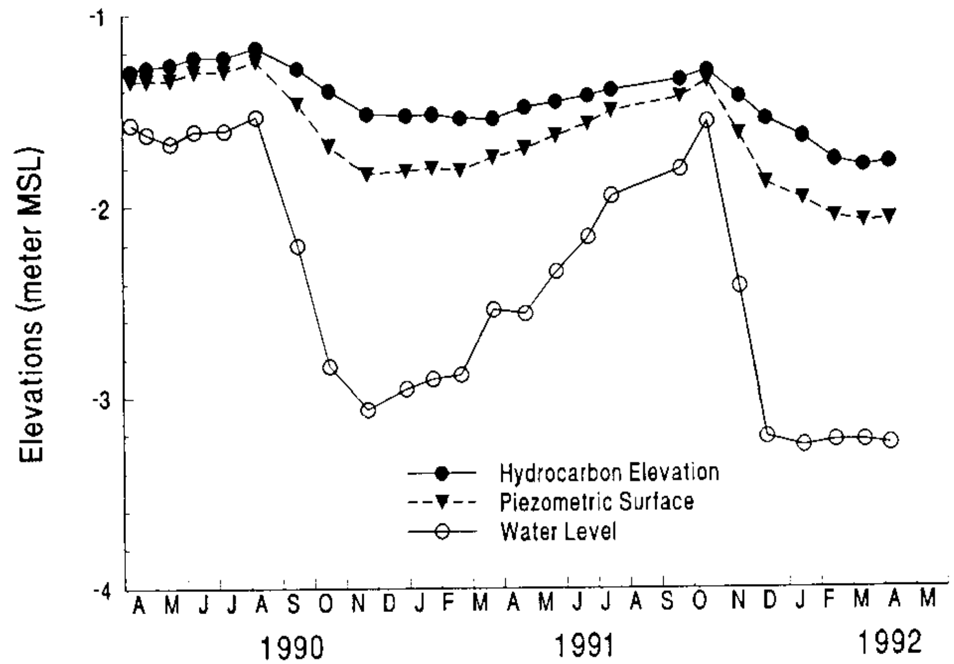
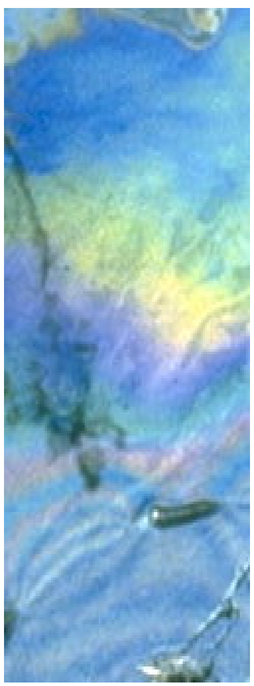


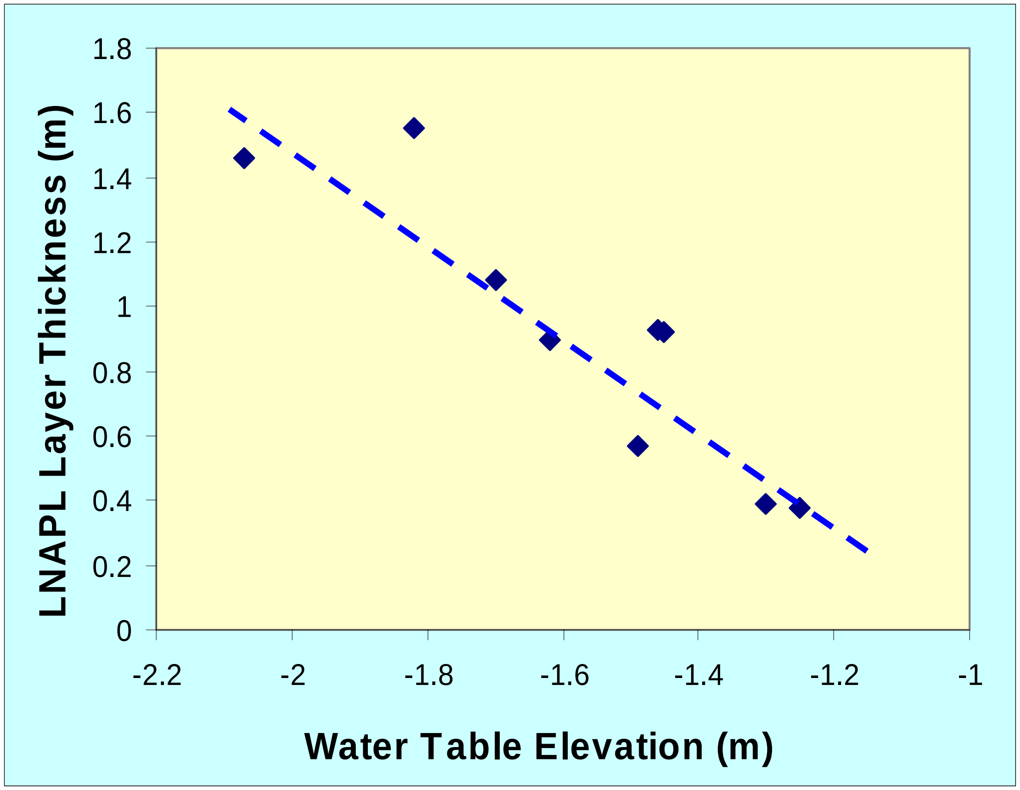
Fig. 14. Fluid level hydrograph, monitoring well MW-8.

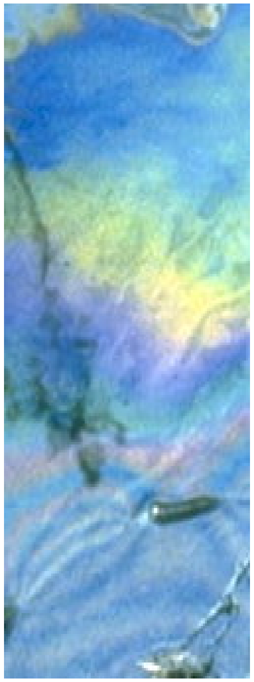
Huntley, Hawk and Corley (1994)



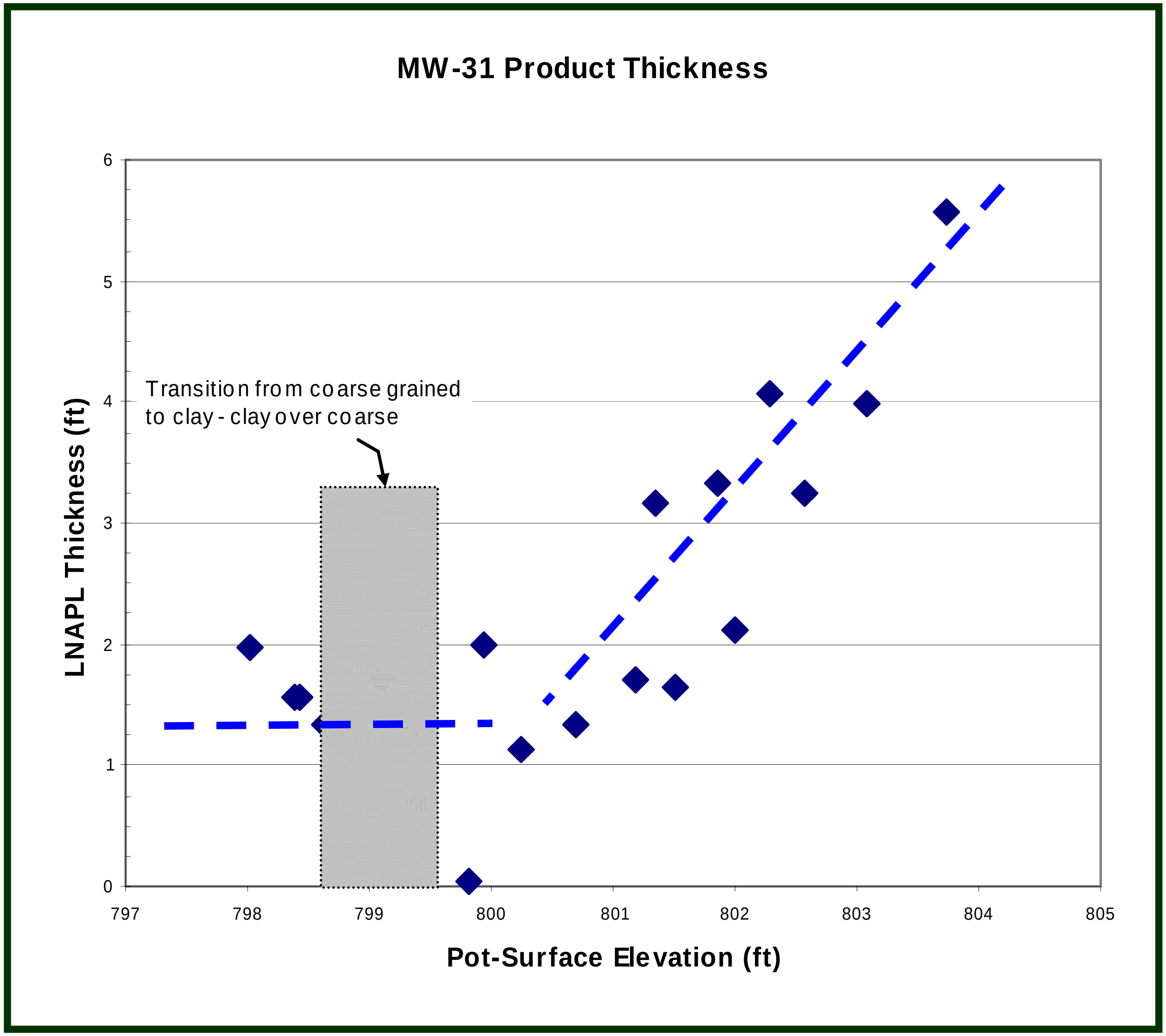
Usual Relationship Between Water Table Elevation and LNAPL Layer Thickness in a Monitoring Well

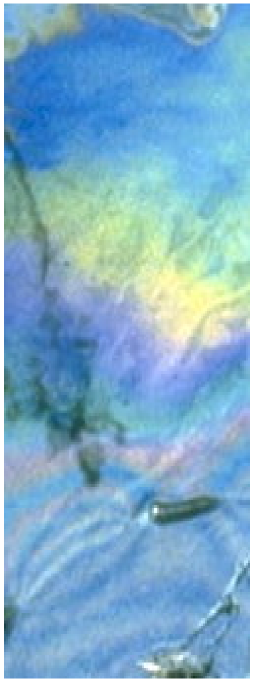
LNAPL Residual is Greater Below the Water Table than in the Vadose Zone (as water table increases LNAPL thickness decreases)





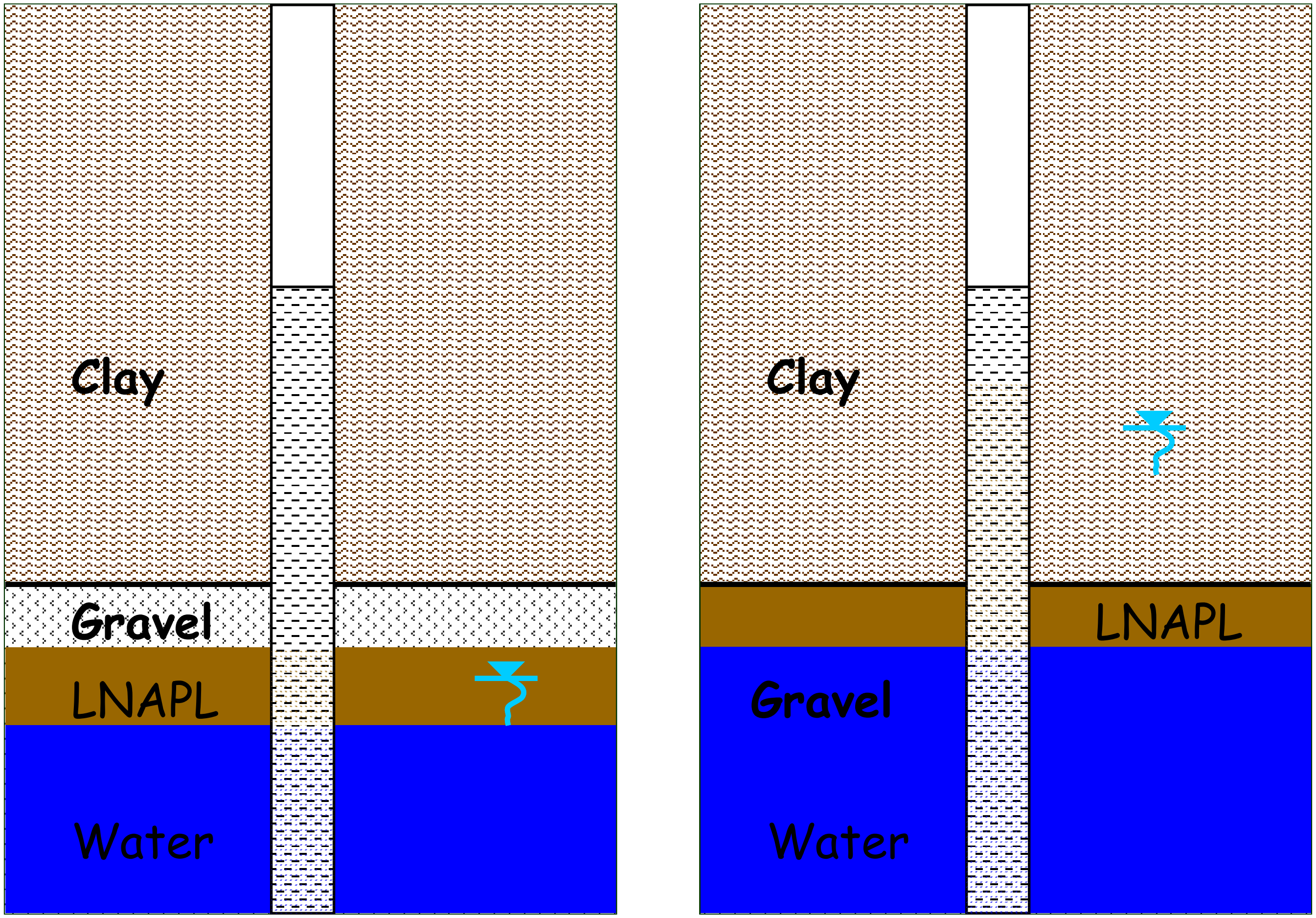
LNAPL Thickness versus Potentiometric Surface Elevation
(site with water table near sand / clay interface)



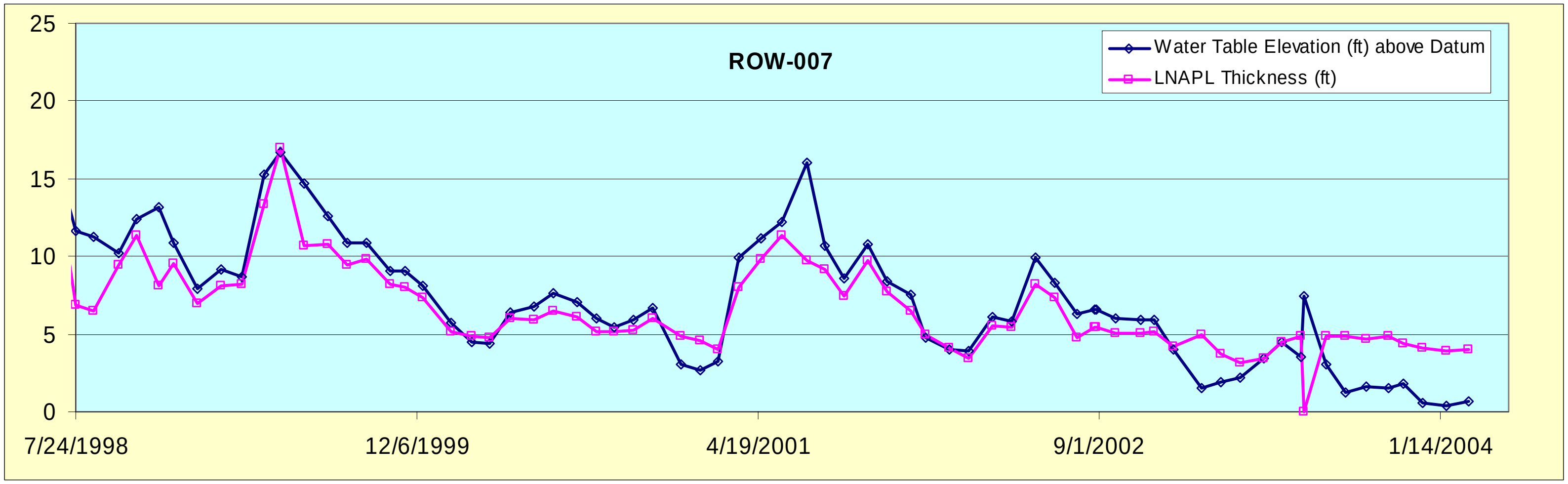


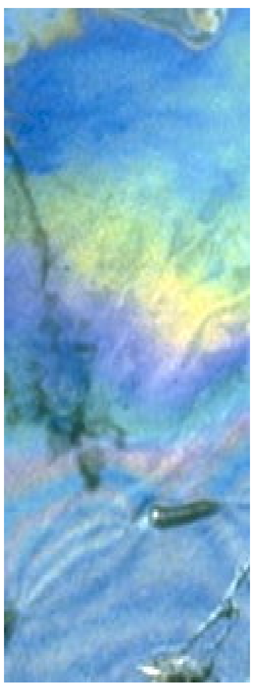
LNAPL in the subsurface

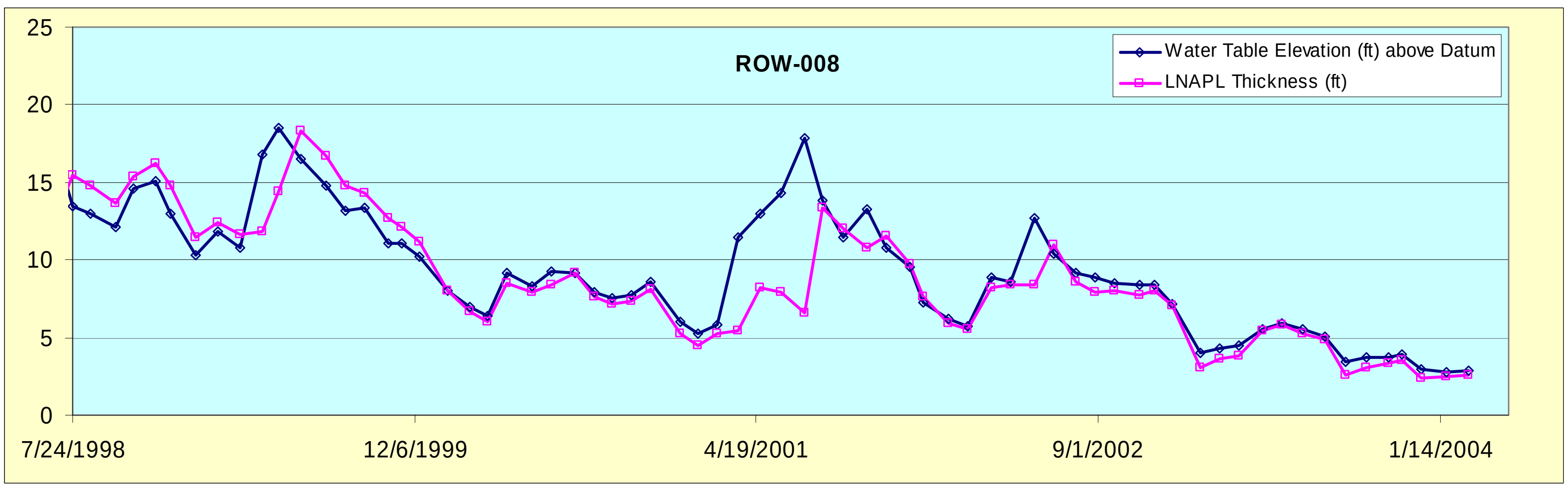
Why LNAPL Thickness Increases with Increase in Water Level? Bottom Filling of Well



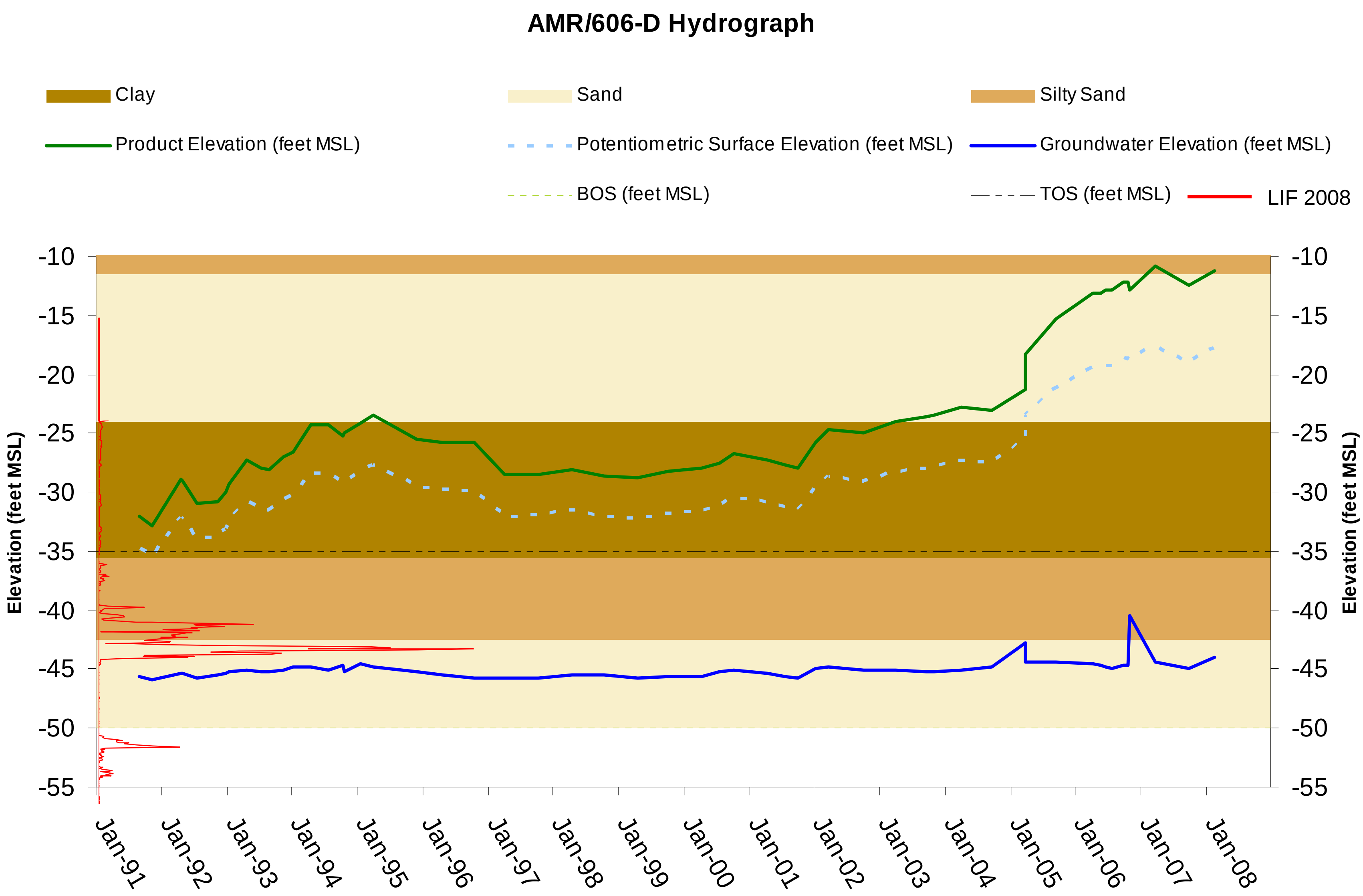
3rd Example with Monitoring Wells Suggesting LNAPL Trapped Beneath FGZ – Bottom Filling of Monitoring Wells





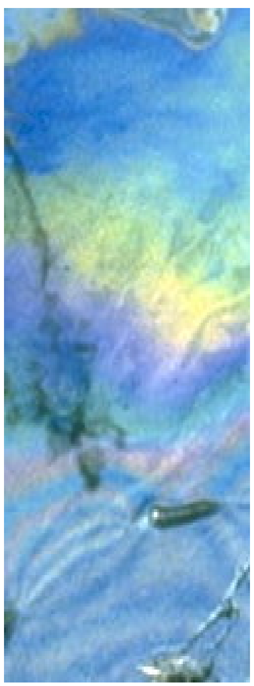


Evidence for confined LNAPL



Key Points

- LNAPL mobility depends on LNAPL saturation, layer thickness, fluid properties, and LNAPL gradient
- LNAPL transmissibility is a good measure of potential mobility
- For oil to enter water saturated pore the oil pressure must exceed the displacement (threshold entry) pressure
- Equilibrium LNAPL thickness in well is critical for understanding the LNAPL condition at a site.
- Variations in LNAPL thickness with water table fluctuation can help explain state of LNAPL (confined, unconfined, or perched)
- We (Mark) are finding that confined LNAPL is pretty common (30 – 50% of sites)



Thank You

LNAPL **in the subsurface**